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THE EFFECT OF THE CUBE TEXTURE COMPONENT ON THE EARING BEHAVIOR OF ROLLED f.c.c. METALS

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Abstract

An application of texture simulation to the formability of rolled f.c.c. sheet is described. Control of the earing behavior of such sheet is crucial to the efficient utilization of material. Cold-rolled f.c.c. metals characteristically give ears at 45° to the rolling direction but it is known that if a large cube component is present before the material is rolled, the severity of the earing is reduced. The cube component, (010)[001], by itself is known to give ears at 90° to the rolling direction and could thus balance a 45° earing tendency. The cube component is unstable to rolling deformation, however, and is generally not observed in heavily cold-rolled f.c.c. metals. Therefore, the challenge is to explain how a large cube component, present prior to rolling, can affect the earing behavior at large rolling reductions. Texture simulation shows that orientations near cube tend to rotate primarily about the rolling direction towards the Goss orientation, (110)[001]. It has been established both experimentally and theoretically that all orientations between the cube and the Goss positions give 90° ears. Therefore, the effect of a prior cube component is due to the special behavior of orientations near cube under rolling deformation.

Introduction

This paper reports the results of the use of a relaxed constraints Taylor model for texture simulation, applied to the problem of earing behavior of rolled f.c.c. metals. The focus of this work was on the effect of the cube component on earing after cold-rolling since this texture component has important consequences for in-plane anisotropy. As has been frequently reported, cold rolled f.c.c. metals give rise to 45° ears, see e.g. Hirsch et al. (1). Annealed f.c.c. metals and their alloys commonly have large components of the cube texture, (010)[001], whose origin is still a matter of controversy. The cube component gives rise to ears at 0° and 90° to the rolling direction, as was shown by Tucker's experiments and calculations on single crystals (2). There is a negative correlation between the severity of 45° earing and the amount of cube component present before rolling as discussed by Kitao et al. (3). Fig. 1 shows this correlation for the aluminum alloy 3004 reported by Doherty et al. (4) where the amount of cube component has been quantified by the severity of 90°earing. The vertical axis is the severity of 45° earing after a 90% cold reduction in rolling. The practical significance of these data is considerable as large volumes of this alloy are used in the as-rolled condition in the beverage can industry.

The cube component is not a stable orientation under rolling, however, and has usually disappeared from the texture after strains of 50% or less. This has been confirmed both theoretically by Dillamore and Katch (5) and experimentally with single crystal experiments by Kohlhoff et al. (6). Hansen and Jensen (7) measured texture component strengths for rolled commercial purity aluminum and the results, Fig. 2, show how rapidly the cube component is lost during rolling. Therefore the puzzle is to explain how the cube component can affect earing even after it is no longer present in the texture. The results of the calculations presented below suggest that it is the fact that the cube component first rotates towards the Goss position which, however, maintains its effect of giving 90° ears.

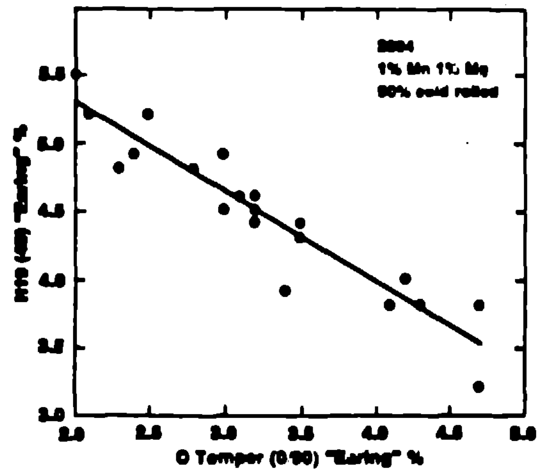

Fig. 1. The relationship between earing (90° ears) in annealed Al 3004 alloy and earing (45° ears) after a subsequent 90% cold reduction by rolling, from Doherty et al. (4).

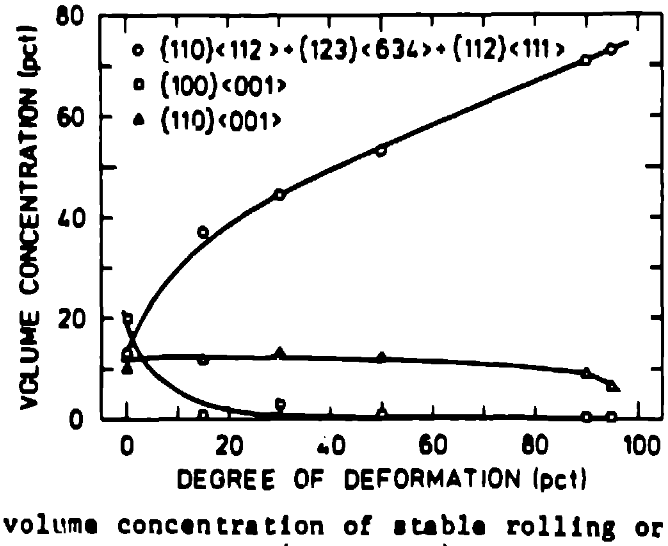

Fig. 2. The volume concentration of stable rolling orientations (circles), the Goss component (triangles) and the cube component (squares) as a function of rolling strain, from Hansen and Jensen (7).

Earing

The experimental observation of earing is that the wall height of a drawn cup varies as a function of position on the periphery of the cup. For rolled sheet, the reference direction for such in-plane anisotropy of the material is chosen to be the rolling direction and the earing pattern is symmetric about this line. It has been noted by several authors that the severity of earing correlates well with ΔR, see e.g. Fukui and Kudo (8), where R is the Lankford coefficient and

$$\Delta R = (R_0 + R_{90})/2 - R_{45} \tag{1}$$

The coefficients at 0°, 45° and 90° to the rolling direction are denoted by R_0, R_{45}, and R_{90}, respectively. There have been several studies in which the texture of a rolled sheet has been determined experimentally, the earing behavior predicted from that texture and a comparison made with the experimental earing behavior, e.g. Kanetake et al. (9). Many assumptions are required for such prediction, however, and it is difficult to obtain quantitative agreement without using adjustable parameters in the model. This paper is concerned with the balance between 45° and 90° earing, however, for which it is sufficient to simulate the variation of R in the rolling plane. Whereas several authors have used experimental textures to predict R values, this work relies entirely on simulated textures.

The reason for the correlation between ΔR and earing behavior is due to the fact that the material at the edge of a drawn cup is effectively undergoing a free compression test. This point can be appreciated by reference to a diagram of a partially drawn cup, Fig. 3.

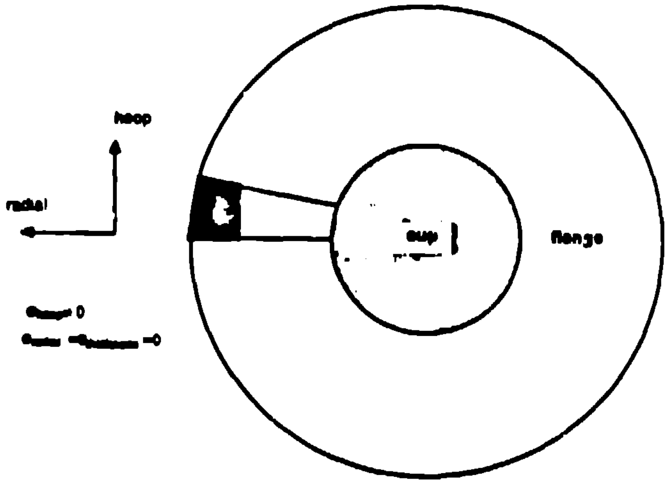

Fig. 3. Diagram of the stress state at the edge of a partially drawn cup.

The only stress that is non-zero at the edge of the blank is the hoop stress since both the radial and the through-thickness stresses must be zero, due to the stress-free boundary conditions of the surface of the thin sheet. At the beginning of the drawing process, when no ears have yet developed, there are also no shear stresses in the sheet. On the other hand, the only restrictions on the strains are (i) that the hoop strain is prescribed and (ii) that the orthotropic symmetry of rolling precludes the development of shear strains that involve the thickness direction. Therefore each element of material on the edge of the blank can be thought of an undergoing a uniaxial compression test, which is the inverse of a tensile test. A high R value means that the material is resistant to thinning in tension or, in compression, that it is resistant to thickening. The more an element of material thickens, however, the narrower it can become in the hoop direction and the further it can be drawn in. Therefore the correlation between R value and earing is that a low R value implies easy thickening and large drawn-in, forming a trough whereas a high R value implies little thickening and a high spot or ear. An important subtlety of this correlation is that the R value measured for a given direction in the rolled sheet gives information about the earing behavior at 90° to that direction.

Computer Simulation of Textures and Plastic Anisotropy

The results reported in this paper are obtained by use of a computer code (10,11,12) that is a general purpose texture simulation tool based on the Taylor model of polycrystal plasticity (13). The Taylor assumption that the strain applied to each grain is exactly that applied to the macrosopic polycrystal has been modified to model the effect of Relaxed Constraints, as introduced by Honneff and Mecking (14,15). The code has been successfully applied, for example, to the simulation of torsion textures by Canova et al. (16). The code calculates the behavior of a set of a few hundred grains and uses the method of Bishop and Hill (17) to locate the point on the single crystal yield surface that will permit each grain to satisfy the imposed strain, see Kocks and Canova (18). In this manner, the flow stress of the polycrystal can be calculated in terms of the critical resolved shear stress for slip on a single slip system, as an average over the grains comprising the polycrystal. This flow stress is the Taylor factor, which is a function of the texture and of the strain path imposed. At large strains, the aspect ratio of the grain shape for any deformation path differs widely from unity. The consequence for rolling is that the normal-rolling and the normal-transverse shear strains can be non-zero without leading to serious compatibility problems. Relaxed Constraints as applied to rolling means that two of the strain component boundary conditions are relaxed. Instead, two stress boundary conditions are substituted for the strain boundary conditions, the consequences of which were explored by Kocks and his co-workers (19,20). For example, the number of slip systems required to satisfy only three strain boundary conditions is only three instead of the minimum of five required by Full Constraints. The method by which the grain shape aspect ratios are calculated and then used to determine the volume fraction of grains that is permitted to deform in relaxed constraints was reported by Tome et al. (10).

The code has also been used to derive yield surfaces from simulated textures by applying suitable sets of strain increments, constant in magnitude but varying in direction, to the aggregate of grains that represents the polycrystal. For each strain direction, an average Taylor factor is calculated, from which a tangent plane to the yield surface can be constructed whose normal is the strain direction and whose distance from the origin is the Taylor factor. The method is discussed in detail by Canova et al. (21) together with the symmetry properties of various types of deformation textures and their associated yield surfaces. Appropriate sections of the yield surface can be used to derive the Lankford coefficient, as discussed by the previous authors, by inspection of the strain components of the normal to the yield surface at the points corresponding to tensile tests in the rolling plane.

Calculations of R-Values

It is not necessary, however, to calculate complete yield surfaces in order to predict the R value for a given tensile test direction. Instead, this work made use of a feature of the code that changes the strain direction until certain imposed stress boundary conditions are satisfied. In the case of the tensile test, this means that, after the grain orientations have been rotated to the direction of interest, an initial tensile test simulation is made with R = 1. If the resulting stress does not correspond to that of a tensile test, that is to say with the only non-zero stress component being that parallel to the tension direction, the strain direction is altered. The method employed is to calculate both the mean value of each stress component and its root-mean-square as a measure of its spread. Then if the boundary value of that stress component differs from the calculated mean value by more than a preset fraction of the spread, the corresponding strain component is changed in the appropriate direction, Fig. 4.

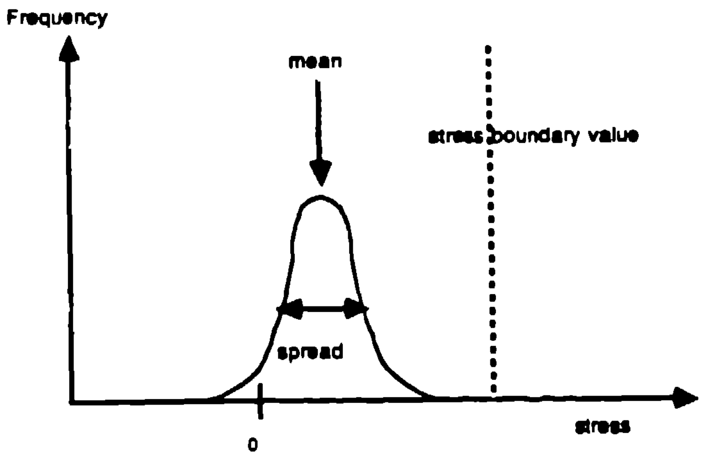

Fig. 4. Diagram of the method used to determine whether to correct the strain direction in order to satisfy a stress boundary condition. If the difference between the mean value of the stress component and the boundary value is greater than the spread in the stress component, a correction is made to the direction of the strain increment imposed on the polycrystal.

After the strain direction has been corrected, the tensile test simulation is re-run. Once a strain direction has been found that satisfies the stress boundary conditions, the R-value is calculated in the usual way as the ratio of the width strain increment to the thickness strain increment.

Simulated Rolling Texture

The texture representation used here to plot the three Euler angles is that proposed by Wenk and Kocks (22). One of the advantages of this polar coordinate representation is that certain highly symmetric orientations, such as the cube, are represented as points rather than as lines as in the conventional Cartesian representation. The convention for Euler angles used here is that of Canova (16) where (ω, θ, ϕ) are the equivalent of $(-\phi_1, -\Phi, -\phi_2)$ in the Bunge notation.

Fig. 5 shows the Crystallite Orientation Distribution COD, for a simulated 800 grain polycrystal after a strain in rolling of 2.5. The initial texture was random and the choice of strain level was based on the data shown in Fig. 1.

The simulated rolling texture shows that the grain orientations have become concentrated along a fibre. The exact position of the fibre varies according to whether the rolling deformation was simulated under Full Constraints or Relaxed Constraints. Fig. 6 is a diagram of this fibre, together with the position of various ideal orientations such as the "S," the Goss and the "copper" positions. At the large strains discussed here, most of the grains of the simulated polycrystal are deforming in Relaxed Constraints.

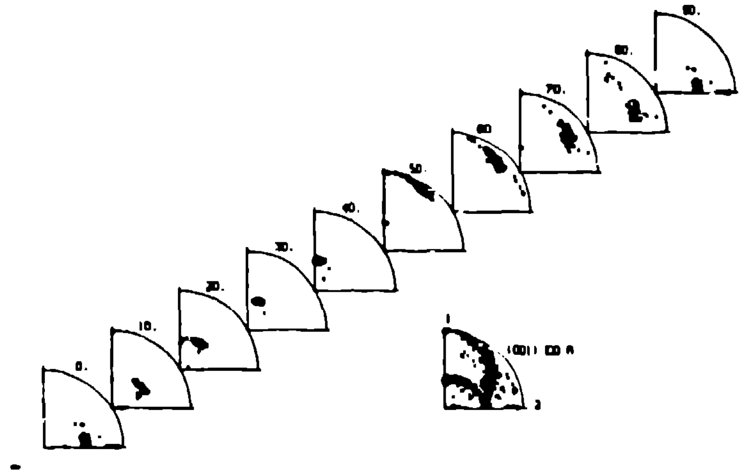

Fig. 5. COD of a simulated rolling texture at a von Mises equivalent strain of 2.5.

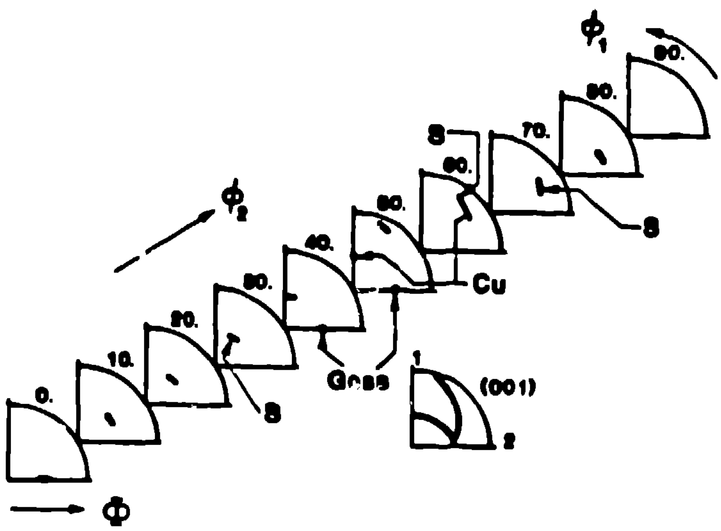

Fig. 6. Diagram of the ideal fibres of rolling orientations with positions of the S, Goss and Cu texture components.

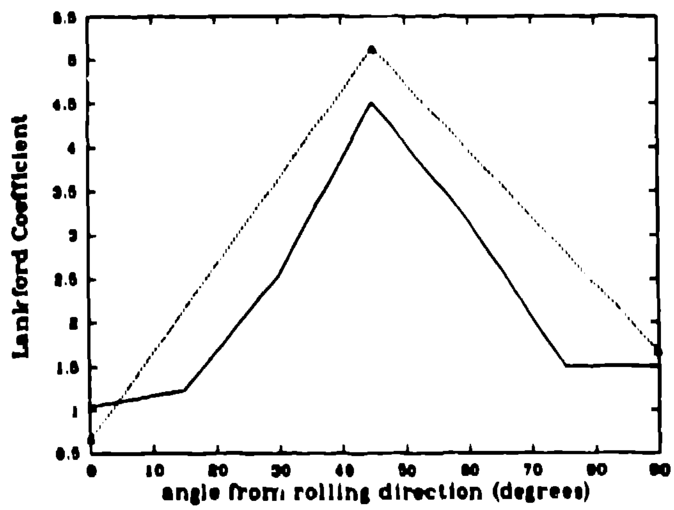

Fig. 7. Plot of R-value versus angle from the rolling direction for a simulated rolling texture, von Mises equivalent strain=3.5, continuous line. Experimental points from Hirsch et al. (1), triangles and dashed line.

The simulated texture shown in Fig. 5 was taken to a von Mises equivalent strain of 3.5 and the R-values calculated from this texture are plotted in Fig. 7. For comparison, the experimental values determined by Hirsch et al. are also plotted (1), which were for copper rolled to a von Mises equivalent strain of 3.5. The simulated R-values are a good match to the experimental values. It should be noted, however, that if Relaxed Constraints are not taken into account and the simulated tension test is done under Full Constraints, the R-value at 45° is much higher.

The Cube Component

The cube component can be modeled by generating a Gaussian spread about the cube position, (010)[001], a technique which has been successfully applied to the modelling of experimental textures by, e.g., Hirsch and Lucke (23). For the 50 grains whose (111) pole figure is displayed in Fig. 8, a Gaussian spread about the cube texture was generated on the computer by taking values at random of ω from $^{-}\pi$ to $^{+}\pi$, ϕ from $^{-}\pi$ to $^{+}\pi$ and sine(θ) from 0 to 1. Then the absolute value of the angle between the reference X axis and the new X axis (crystal X axis) was compared to a random number with a Gaussian distribution, zero mean and a standard deviation of 5 degrees. If the angle is smaller than the Gaussian random number, the set of Euler angles is accepted. Choosing sine(θ) randomly rather than theta ensures that uniform coverage of orientation space is obtained.

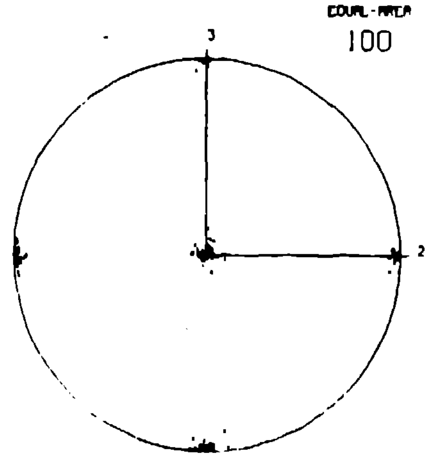

Fig. 8. (100) pole figure of 50 grains comprising a simulated cube component with a 5° spread about (010)[001].

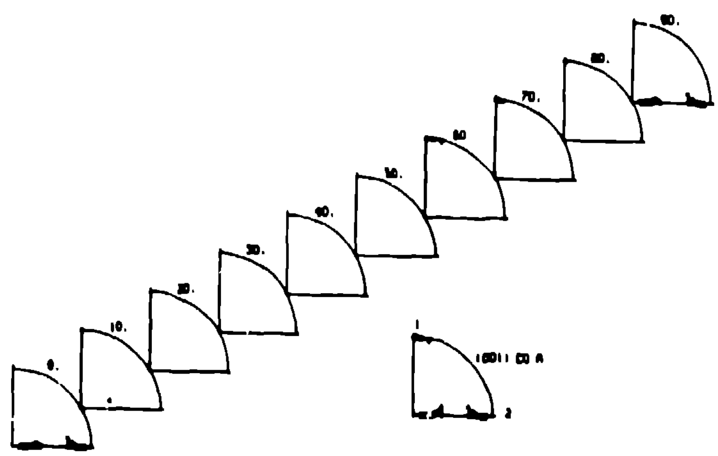

Fig. 9. COD of the texture of the cube component polycrystal after a von Mises equivalent strain of 2.5 in rolling, equivalent to a reduction in thickness of 89%.

This polycrystal was then subjected to the same strain as the previous system, producing the texture displayed in Fig. 9. In contrast to the texture obtained from an initially random polycrystal, the texture obtained from the cube component is a fibre texture based on rotations about the rolling direction. This result is in agreement with the theoretical work by Dillamore and Katoh (5) who showed that the cube component tends to rotate about the rolling direction towards the Goss position. They also showed that orientations related to the cube by a rotation about the normal direction would rotate towards the cube position, showing that it is possible for cube oriented material to be generated by rolling from cube-related orientations. The topic of orientation changes in the vicinity of the cube component was discussed in detail by Rollett (24) who verified the Dillamore and Katoh results for Full Constraints but found that Relaxed Constraints tended, among other effects, to destabilize the cube collection mechanism mentioned above. Experimental support for this theoretical work was reported by Kohlhoff et al. (6) who rolled cube-oriented single crystals of copper. They found that up to 50% reduction, the material developed the rolling direction fibre simulated in Fig. 9. Above this strain, the reorientation was more complex and at high strains, most of materials was close to the S orientation, (123)[634]. Tucker (2) showed that all orientations on the fibre between (010)[001] and (110)[001] give rise to 90° ears. Therefore the texture shown in Fig. 9 should also give rise to 90° ears. The variation of R-value with angle calculated from this texture has the anticipated minimum at 45°, corresponding to a trough in the earing pattern, Fig. 10.

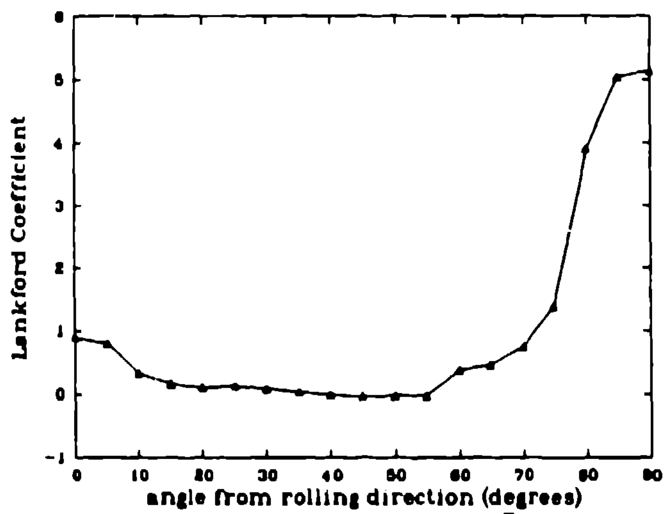

Fig. 10. Variation of R value with angle in the rolling plane for the cube component after a von Mises equivalent strain of 2.5.

Combined Textures

The effect of adding the cube component to the random component and rolling the combined polycrystal is easily modeled by adding the one set of grains to the other. Fig. 11 shows the variation of R-value with angle in the rolling plane and with volume fraction of the cube component. As expected, the addition of the grains derived from the cube component reduces the predicted severity of the 45° ears due to the 90° earing tendency of the added material. It may be observed that for these simulated textures, the initial volume fraction of cube component must be as high as 20% for a completely balanced texture. This would appear to be a reasonable conclusion in the light of the experimental data shown in Fig. 1 where the 45° earing at 90% cold reduction is not eliminated even for the highest initial cube content.

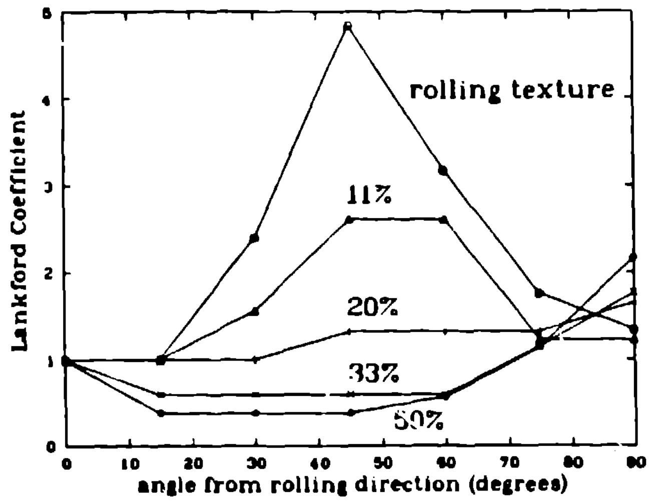

Fig. 11. Variation of R-value with angle in the rolling plane and with volume fraction of material that was initially cube oriented. The simulated textures were at a von Mises equivalent strain of 2.5.

Conclusion

The conclusion from the work presented here is that a high volume fraction of the cube component reduces the 45° earing of cold-rolled f.c.c. metals because of the tendency of the cube component to reorient along a fibre based on rotation about the rolling direction. This fibre of orientations gives rise to 90° ears which balance the normal 45° ears found experimentally and predicted by the simulations. For the simulated rolling textures reported, a large initial volume fraction of the cube component is required to completely balance 90° against 45° ears.

Acknowledgements

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